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RESEARCH ARTICLE

EVOLUTION OF RADIATION SAFETY IN MEDICINE: A BIBLIOMETRIC INSIGHT INTO RESEARCH TRENDS (1990-2023)

Uğur UĞRAK [*]
Selahattin AKYÜZ [**]

ABSTRACT

This study aims to conduct a bibliometric analysis of the publications on radiation safety in healthcare. The data in the study was obtained from the Web of Science, and bibliometric analysis was performed with SciMAT software. To filter the literature from the database, the search criteria "radiation safety," or "radiation protection" (topic), and "medicine" (search in all fields), and "articles" (document types) were used between 1990 and 2023. Four-thousand-four-hundred-thirty-nine (4439) publications meeting these criteria were found. The most frequent keyword was "radiation safety" (n=1250). The countries with the most publications in the literature were the United States of America (n=1172) and Germany (n=519). Türkiye (n=145) ranked fifteenth. Studies on passive protection in radiation protection came to the fore in the 1990s. Scientific studies focused on high radiation exposure modalities, such as computed tomography and interventional radiology, in the 2000s. Since 2010, studies on active radiation protection have come to the fore. A changing trend can be seen in radiation safety in medicine, from an employee-oriented approach to a patient- and employee-oriented approach and from passive protection to passive and active protection measures. Optimization studies are gaining importance, especially in interventional radiology and computed tomography. This study provides a comprehensive bibliometric analysis of the scientific literature on radiation safety in medicine, revealing the field's historical development and current research trends. By identifying significant gaps and future focal points in the research area, this analysis offers valuable insights for academics, policymakers, and healthcare professionals, thus contributing significantly to the literature.

Keywords: *Healthcare, radiation, radiation protection, health policy*

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ARAŞTIRMA MAKALESİ

TIPTA RADYASYON GÜVENLİĞİNİN EVRİMİ: ARAŞTIRMA TRENDLERİNE BİBLİYOMETRİK BİR BAKIŞ (1990-2023)

Uğur UĞRAK*
Selahattin AKYÜZ**

ÖZ

Bu çalışmanın amacı sağlık hizmetleri alanında radyasyon güvenliğine yönelik yapılan çalışmaların bibliyometrik analizini yapmaktır. Araştırmada kapsamına alınan veriler Web of Science veri tabanından indirilmiş ve bibliyometrik analizi SciMAT yazılımı ile yapılmıştır. İlgili literatürün veri tabanından filtrelenmesi için, 1990-2023 yılları arasında "radyasyon güvenliği", "radyasyondan korunma" (konu) ve tıp (tüm alanlarda arama), makale (belge türleri)" arama kriterleri kullanılmıştır. Bu kriterlere uyan 4439 makaleye ulaşılmıştır. En sık kullanılan anahtar kelime "radyasyon güvenliğidir" (n=1250). İlgili literatürde en çok yayın yapan ülkeler Amerika Birleşik Devletleri (n=1172) ve Almanya'dır (n=519). Türkiye 145 yayınla on beşincidir. 1990'lı yıllarda radyasyondan korunmada pasif korunma tedbirlerine yönelik çalışmalar öne çıkarken, 2000'li yıllarda bilgisayarlı tomografi ve girişimsel radyoloji gibi radyasyona maruziyetin yüksek olduğu modalitelerde bilimsel çalışmaların odaklandığı tespit edilmiştir. 2010 yılından günümüze ise radyasyondan aktif korunma yöntemleri ile ilgili çalışmalar ön plana çıkmaktadır. Tıpta radyasyon güvenliğinde çalışan odaklı yaklaşımdan hasta ve çalışan odaklı yaklaşıma, pasif korunma önlemlerinden pasif ve aktif koruma önlemlerine doğru bir değişim eğilimi görülmektedir. Özellikle girişimsel radyoloji ve bilgisayarlı tomografi gibi alanlarda optimizasyon çalışmaları önem kazanmaktadır. Bu çalışma, sağlık hizmetlerinde radyasyon güvenliği konusundaki bilimsel literatürün bibliyometrik analizi ile alandaki tarihsel gelişimi ve mevcut araştırma eğilimlerini kapsamlı bir şekilde ortaya koymaktadır. Bu analiz, araştırma alanındaki önemli boşlukları ve gelecekte odaklanılması gereken konuları belirleyerek, akademisyenler, politika yapıcılar ve sağlık profesyonelleri için değerli bilgiler sunması yönü ile literatüre katkı sunacağı değerlendirilmektedir.

Anahtar Kelimeler: *Sağlık hizmetleri, radyasyon, radyasyondan korunma, sağlık politikası*

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I. INTRODUCTION

Since the invention of ionizing radiation, it has been actively used in many areas and makes life easier. Industry, security (Silva, 2015) agriculture (Clarke, 1959; Djezzar, 2018) archaeology (Cooper et al., 1998) nuclear energy, and medicine (Warren, 1959) are a few of them. Its use in medicine is significant, especially in diagnosis and treatment (Martin & Sutton, 2015). If we list the services in the fields of medicine, radiography (Parks & Williamson, 2002), computed tomography (CT) (Armao & Smith, 2014), nuclear medicine, interventional radiology, and cardiology (Al Kharji et al., 2019; Bartal et al., 2014), mammography (Mettler et al., 1996) and radiotherapy can be said.

Ionizing radiation is known for its benefits and adverse health effects (Martin & Sutton, 2015). The short- and long-term effects of ionizing radiation on human health are important topics in the literature. The effects of radiation can be discussed under stochastic and deterministic effects (Alhasan & Aalam, 2022; Purohit et al., 2021; Suzuki et al., 2009; Wilson-Stewart et al., 2023).

The effects that occur due to the cumulative effects of radiation on human DNA over time are expressed as stochastic effects. Stochastic effects do not have a safe radiation dose limit. In other words, it may cause different results in different doses in each unique individual (Sun et al., 2013). Stochastic effects often appear as cancer cases (Bennardo et al., 2021; Purohit et al., 2021).

Deterministic effects of radiation can be defined as health problems that occur acutely in the area where radiation is administered. Deterministic effects can often appear as tissue damage. There is more comprehensive evidence in the literature regarding the deterministic effects of radiation than stochastic ones (Balter et al., 2010).

As can be understood from the literature findings above, radiation affects health workers and patients, which can cause significant health problems (Andreassi et al., 2005; Andreassi et al., 2007; Beir, 2005; Blettner et al., 2007; Ciraj- Bjelac et al., 2010; Finkelstein, 1998; Vano et al., 2010). In this respect, meticulously following the protective measures to justify radiation use is crucial. Health professionals must comply with many safety protocols and use equipment to protect themselves and their patients from the adverse effects of radiation (Dalvi et al., 2022; Fiorilli et al., 2020; Hinton, 2020; Uthirapathy et al., 2022). The attitudes and behaviours of healthcare professionals are important in medical radiation device usage for protecting patient and employee health against radiation effects (Harris et al., 2019; Moore, 2021; Partap et al., 2019). Radiation safety studies in medicine are the core of this study. This study aims to make a bibliometric analysis of scientific studies on radiation safety in medicine. The findings obtained from this study are to present essential findings about the literature trend of radiation safety in medicine to researchers, healthcare administrators, and providers.

II. MATERIAL AND METHOD

This section includes methodological information about data acquisition and exclusion criteria, data grouping, data analysis, and interpretation during the bibliometric analysis process. Bibliometric analysis is defined as a methodology that can give information about the literature flow, publication trends, author, and country collaborations by using features of publications in the literature, such as field, subject, author, keyword, citation, and region (Donthu et al., 2021). Academics use bibliometric analysis to uncover current issues, discover research trends, and identify leading authors, topics, and regions. Bibliometric analysis is instrumental when the data is large (Kurutkan & Orhan, 2018). With these aspects of bibliometric analysis, bibliometric analysis has been evaluated as a suitable research method to study radiation safety in medicine. Ethical approval was not required for this study because it was conducted with publicly available WOS data.

2.1. Data Selection

The data in the research were downloaded from the Web of Science (WoS) Core Collection database. "Radiation safety" (Topic) OR "radiation protection" (Topic) and Medicine (Search within all fields) and Article (Document Types)" search criteria were used to filter the related literature from the database. All studies within the search strategy were examined without time limitations. Based on this search criteria, 4439 articles were obtained. The data of these publications were downloaded in "plain text" format. The data were uploaded to the SciMAT program for analysis. Fifty-seven (57) articles without keywords, dated 1989 and before, were excluded. Before the analysis, 11406 keywords of the articles were categorized considering the singular/plural usage and abbreviations.

2.2. Data Categorization

The analyses were carried out with the years allocated for 1990-1999, 2000-2009, and 2010-2023. There are 350 articles from 1990 to 1999, 785 from 2000 to 2009, and 3247 from 2010 to 2023.

2.3. Data Analysis and Interpretation

Configurations of the SciMAT program in the analysis are [Unit of analysis: Words (authorRole = true , sourceRole = true , addedRole = true); Kind of network: Co-occurence ; normalization measure : equivalence index ; Cluster algorithm : Centers simple , Max cluster size: 6, Min cluster size: 1; Evolution measure : Inclusion index ; overlapping measure : Inclusion index]. The research analyses were conducted and presented two approaches: performance analysis and science mapping. Publication metrics, citation metrics, and publication-citation metrics were used in the performance analysis. The science mapping process was managed with network analysis. Network analysis findings were visualized with strategic diagrams, thematic networks, overlap maps, and thematic development map visuals (Donthu et al., 2021). The theme sizes in the visuals are changed with the publication number. The themes' quality is evaluated by the number of publications and citations and the h-index values. The levels of centrality and intensity have a very important role in the theme's placement in the strategic diagrams. Themes with stronger external relations, more centrality, are placed on the right side of the diagram, while the themes with stronger internal relations, more intense, are placed on the upper side of the diagram. According to these features, themes can be placed in 4 different areas.

- Motor themes with high centrality and intensity are in the upper right area,
- Emerging or disappearing themes with low centrality and density are in the lower left area.
- Basic and transformational themes with high centrality and low intensity are in the lower right area.
- Advanced and isolated themes with low centrality and density are in the upper left area.

Thematic networks reveal the relationships between the themes. The thickness of the lines is shaped according to the strength of the relationship. The overlap map visualizes the quantitative change of the keywords during the analysis periods. The thematic development map presents horizontal relations of the themes between the periods. The line thickness is changed with the relationship strength. Whereas solid lines present that the exact keywords are used between the themes as the theme names, dashed lines show that only common keywords are shared, not the theme names (Akyüz et al., 2021; Cobo et al., 2011; Cobo et al., 2012; Cobo et al., 2015; Martínez et al., 2015; Murgado-Armenteros et al., 2015).

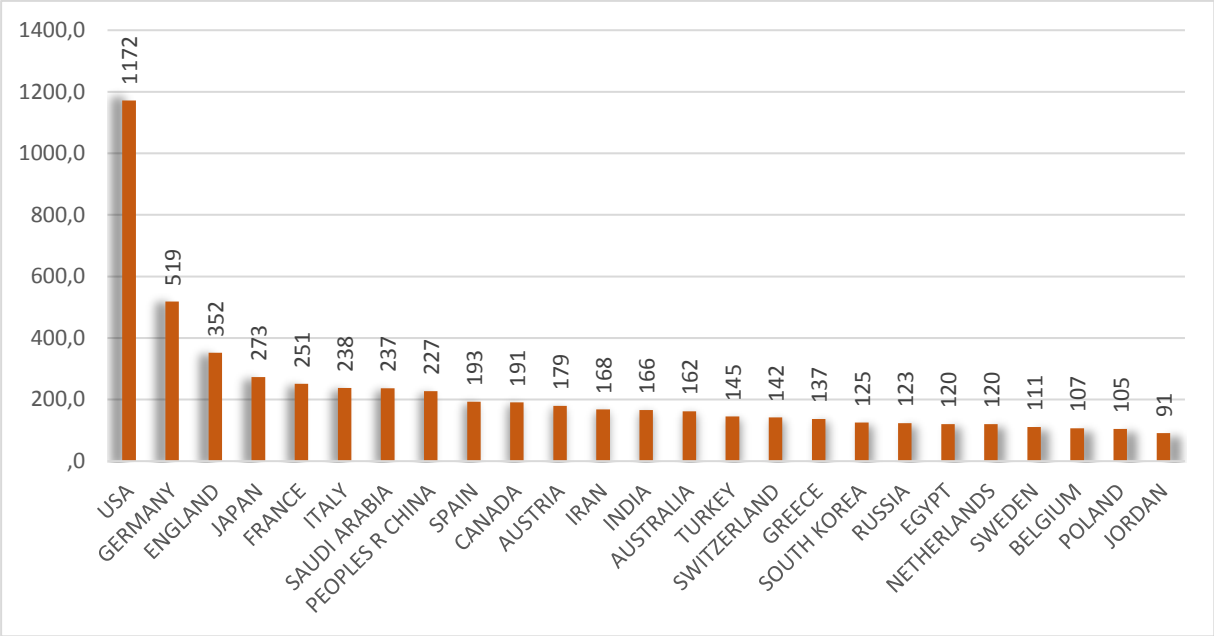
III. RESULTS

The findings are presented with general performance findings, followed by 1990-1999, 2000-2009, and 2010-2023.

3.1. General Performance Findings

As seen in Figure 1, the total publication (TP) about the subject by country, the USA is in first place with 1172 articles, significantly more publications than other countries. Germany follows the USA with 519 articles. England is third with 352 articles. Türkiye is 15th with 145 articles.

Figure 1. Number of Articles by Country (Top 25 Countries)



The total citations (TC) for the articles are 71010. The average citation (AC) is 16. When self-citations are excluded, TC is 63221, and the h-index (h) is 98. The most prolific authors and most frequent keywords in the articles are presented in Table 1. The top 3 most influential publications are (Allison et al., 2006), (Allison et al., 2016), and (Mettler Jr et al., 2009). Additionally, the most prolific authors are Sayyed MI (n=84), Vano E (n=79), and Tekin HO (n=49). The most frequent keywords are “radiation-protection” (n=1250), followed by “exposure” (n=626) and “radiation” (n=393) keywords.

Table 1. General Performance Findings

Rank	The Most Influential Publications	Citation (n)
1	Allison, J., Amako, K., Apostolakis, J., Araujo, H., Dubois, P. A., Asai, M., . . . Chytracek, R. (2006). *Geant4 developments and applications.* IEEE Transactions on Nuclear Science, 53(1), 270-278.	4205
2	Allison, J., Amako, K., Apostolakis, J., Arce, P., Asai, M., Aso, T., . . . Barrand, G. (2016). *Recent developments in Geant4. Nuclear instruments and methods in physics research section A*: Accelerators, Spectrometers, Detectors and Associated Equipment, 835, 186-225.	1783
3	Mettler Jr, F. A., Bhargavan, M., Faulkner, K., Gilley, D. B., Gray, J. E., Ibbott, G. S., . . . Stabin, M. G. (2009). *Radiologic and nuclear medicine studies in the United States and worldwide: frequency, radiation dose, and comparison with other radiation sources—1950–2007.* Radiology, 253(2), 520-531.	591
4	Bolch, W. E., Eckerman, K. F., Sgouros, G., & Thomas, S. R. (2009). *MIRD pamphlet No. 21: a generalized schema for radiopharmaceutical dosimetry--standardization of nomenclature.* J Nucl Med, 50(3), 477-484. doi:10.2967/jnumed.108.056036	482
5	Cardis, E., Vrijheid, M., Blettner, M., Gilbert, E., Hakama, M., Hill, C., . . . Veress, K. (2005). *Risk of cancer after low doses of ionizing radiation: retrospective cohort study in 15 countries*. BMJ, 331(7508), 77. doi:10.1136/bmj.38499.599861.E0	414
Rank	**The Most Prolific Authors**	**Article (n)**
1	Sayyed MI	84
2	Vano E.	79
3	Tekin HO.	49
4	Dauer LT	36
5	Chida K.	34
Rank	**Most Frequent Keywords**	**(n)**
1	Radiation-Protection	1250
2	Exposure	626
3	Radiation	393
4	Dosimetry	374
5	Radiation-Safety	357
6	Computed-Tomography	348
7	Ionizing-Radiation	332
8	Radiation-Exposure	329
9	Risk	296
10	Cancer	240

3.2. 1990-1999 Period

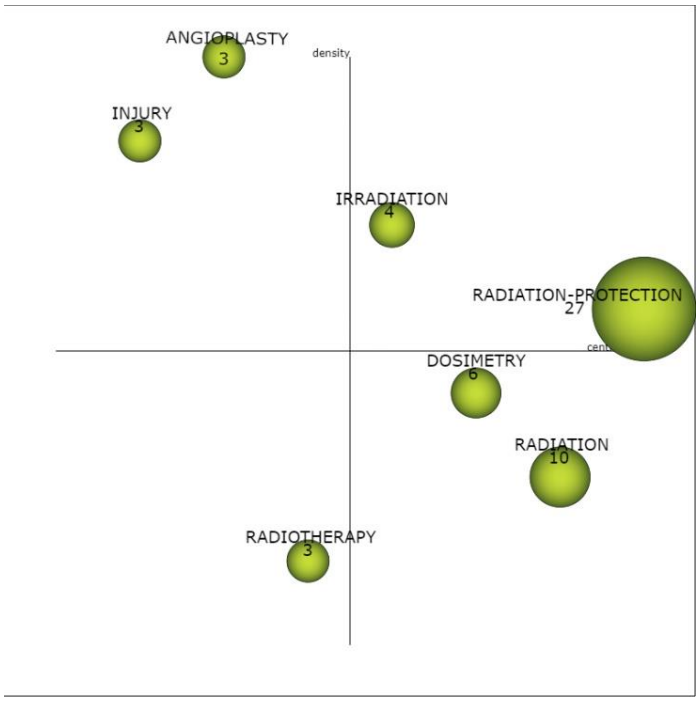
As presented in Table 2, seven themes emerged for the 1990-1999 period. The theme with the most publications (n=27) in 1990-1999 is “radiation protection.”. This theme’s TC is 475, and its h-index value is 10. The second theme with the most publications (n=10) in this period is “radiation.” This theme’s TC is 379, and its h-index value is 8.

Table 2. Theme Performance Findings of 1990-1999

Theme Name	Publications (n)	Total Citations (n)	H-Index	Centrality	Density
Radiation-Protection	27	475	10	18.48	9.32
Radiation	10	379	8	3.11	6.25
Angioplasty	3	359	3	0.00	100.00
Dosimetry	6	266	5	0.79	8.02
Injury	3	145	3	0.00	100.00
Irradiation	4	58	4	0.25	10.94
Radiotherapy	3	52	3	0.08	4.69

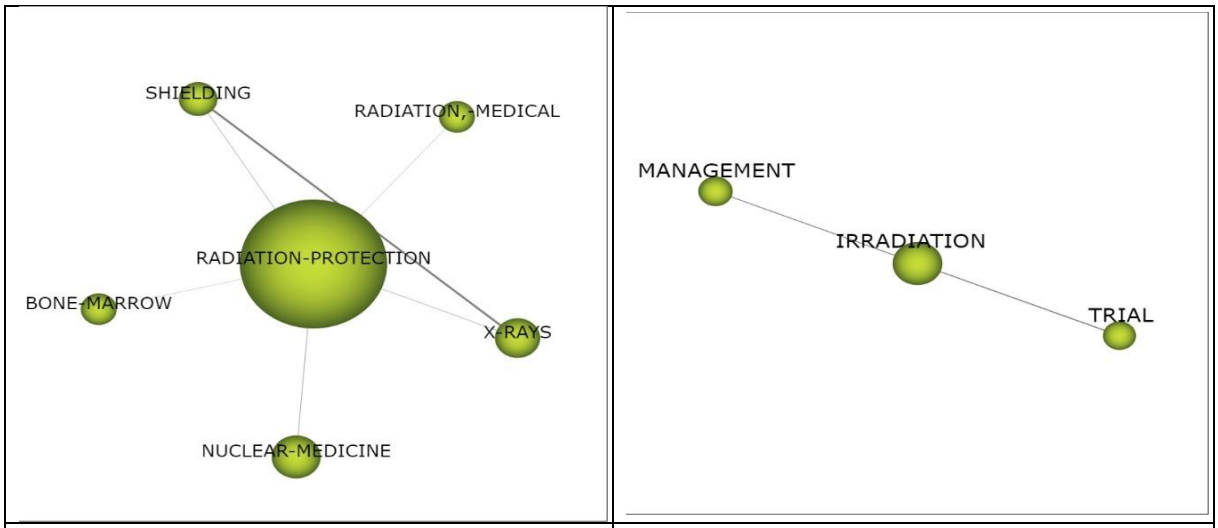
Figure 2 shows two engine themes: "radiation protection" and "irradiation." Two are isolated and advanced themes; "angioplasty" and "injury." Two are basic and transformational themes; "dosimetry" and "radiation." The last one is an emerging or disappearing theme, "radiotherapy."

Figure 2. Strategic Diagram (1990-1999)



As seen in Figure 3, "Radiation protection" is related to "radiation medical," "X-ray," "nuclear medicine," "bone marrow," and "shielding" themes. "Irradiation" is related to "management" and "trial" themes.

Figure 3. Thematic Network of the Two Influential Themes in 1990-1999



Radiation Protection	**Irradiation**

3.3. 2000-2009 Period

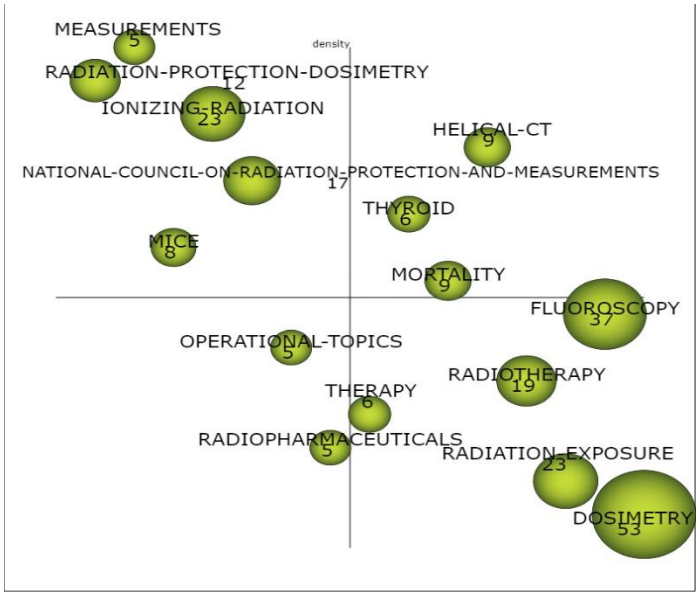
Based on findings in Table 3, fifteen themes emerged in the strategic diagram for 2000-2009. The theme with the most publications (n=53) in 2000-2009 is "dosimetry." This theme's TC is 1303, and its h-index value is 21. The second theme with the most publications (n=37) in the same period is "fluoroscopy. "This theme's TC is 1309, and its h-index value is 18.

Table 3. Theme Performance Findings of 2000-2009

Theme Name	Publications (n)	Total Citations (n)	H-Index	Centrality	Density
Fluoroscopy	37	1309	18	4.07	6.72
Dosimetry	53	1303	21	9.2	3.55
Radiation-Exposure	23	987	14	2.6	4.41
Ioning-Radiation	23	953	16	0.26	13.51
Radiation-Protection-Dosimetry	12	871	11	0	26.47
National - Council -On- Radiation - Protection-And-Measurements	17	838	14	0.36	11.62
Radiotherapy	19	579	11	1.98	4.97
Helical-Ct	9	481	8	1.78	12.42
Mice	8	410	8	0.11	9.2
Mortality	9	248	8	1.33	7.14
Radiopharmaceuticals	5	194	4	0.6	4.46
Thyroid	6	102	5	0.7	11.11
Therapy	6	79	4	0.64	4.55
Measurements	5	37	3	0	50
Operational-Topics	5	11	2	0.39	6.31

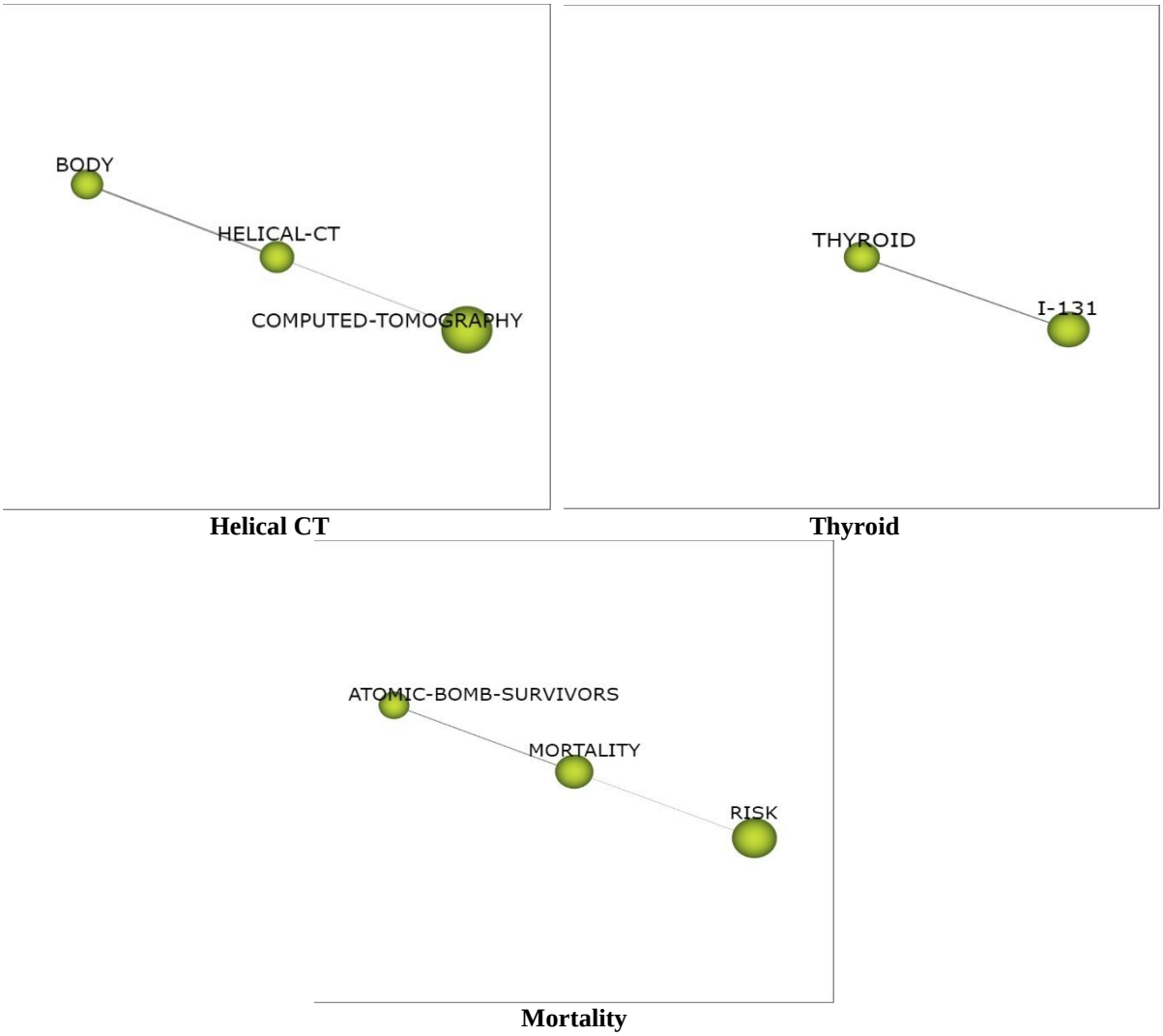
Figure 4 indicates three of these are motor themes; "Helical CT," "thyroid," and "mortality." Five are isolated and advanced themes; "measurement," "radiation," "protection dosimetry," "ionizing radiation," "National Council on Radiation Protection, and "measurements" and "mice." Five are basic and transformational themes; "fluoroscopy," "radiotherapy," "therapy," "radiation exposure" and "dosimetry." Two are appearing or disappearing themes; "operational topics," and "radiopharmaceuticals."

Figure 4. Strategic Diagram (2000-2009)



The thematic network (Figure 5) presents relationships of three influential themes in 2000-2009. "Helical CT" is related to "body" and "computed tomography" themes. The "Thyroid" theme is related to the "I-131" theme, and the "mortality" theme is linked to "atomic bomb survivors" and "risk" themes.

Figure 5. Thematic Network of the Two Influential Themes in 2000-2009



3.4. 2010-2023 Period

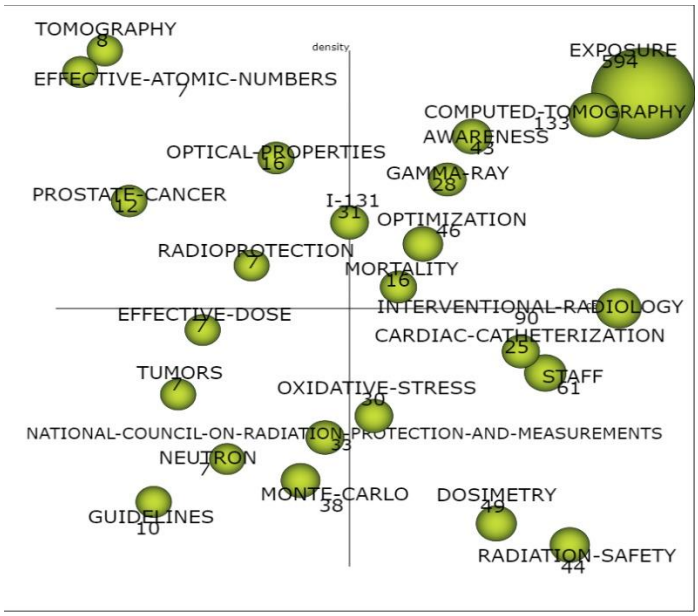
As seen in Table 4, twenty-four themes emerged for 2010-2023. In this period, the theme with the most publications (n=594) is "exposure." This theme's TC is 6,886, and the h-index value is 40. The second theme with the most publications (n=133) in this period is "computed tomography." This theme's TC is 1698, and the h-index value is 21.

Table 4. Theme Performance Findings of 2010-2023

Theme Name	Publications (n)	Total Citations (n)	H-Index	Centrality	Density
Exposure	594	6886	40	41.97	7.41
Computed-Tomography	133	1698	21	14.52	7.31
Interventional-Radiology	90	881	17	15.72	3.59
Staff	61	773	13	9.21	2.96
Dosimetry	49	790	16	5.56	1.18
Optimization	46	570	14	4.64	4.7
Radiation-Safety	44	616	12	11.75	0.88
Awareness	43	292	9	4.93	6.52
Monte-Carlo	38	352	10	2.03	1.69
National-Council-On-Radiation-Protection-And-Measurements	33	372	13	3.09	2.4
I-131	31	145	6	3.74	4.94
Oxidative-Stress	30	426	11	3.83	2.86
Gamma-Ray	28	635	14	4.9	5.23
Cardiac-Catheterization	25	333	9	7,00	2.99
Optical-Properties	16	265	9	2.01	5.32
Mortality	16	464	8	3.94	3.64
Prostate-Cancer	12	121	6	0.27	4.96
Guidelines	10	174	5	0.31	1.56
Tomography	8	78	4	0.24	16.84
Effective-Atomic-Numbers	7	250	5	0,00	14.41
Radioprotection	7	255	4	1.04	4.00
Effective-Dose	7	80	4	0.6	3.09
Tumors	7	76	4	0.48	2.92
Neutron	7	235	7	0.89	1.88

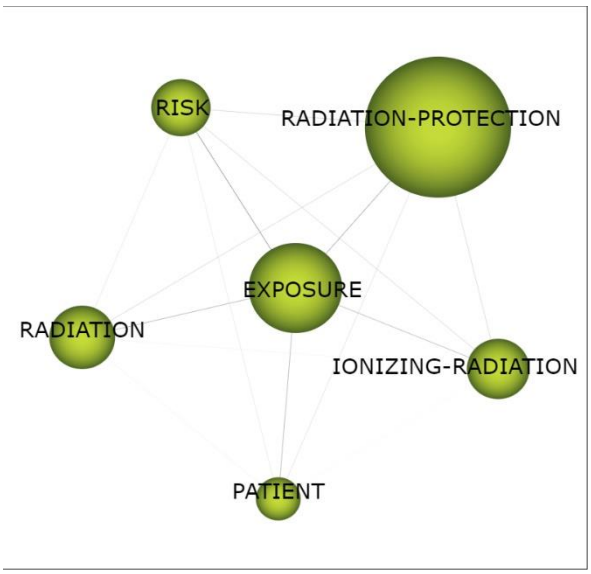
The strategic diagram (Figure 6) shows eight of these themes are engine themes; “exposure,” “computed tomography,” “awareness,” “gamma ray,” “I-131”, “optimization,” “mortality,” and “interventional radiology.” Five are isolated and advanced themes; “tomography,” “effective atomic numbers,” “optical properties,” “prostate cancer,” and “radioprotection.” Five are basic and transformational themes; “cardiac catheterization,” “staff,” “oxidative stress,” “dosimetry,” and “radiation safety. “Six are appearing or disappearing themes; “effective dose,” “tumors,” “National Council on Radiation Protection and Measurements,” “neutron,” “Monte Carlo,” and “guidelines.”

Figure 6. Strategic Diagram (2010-2023)

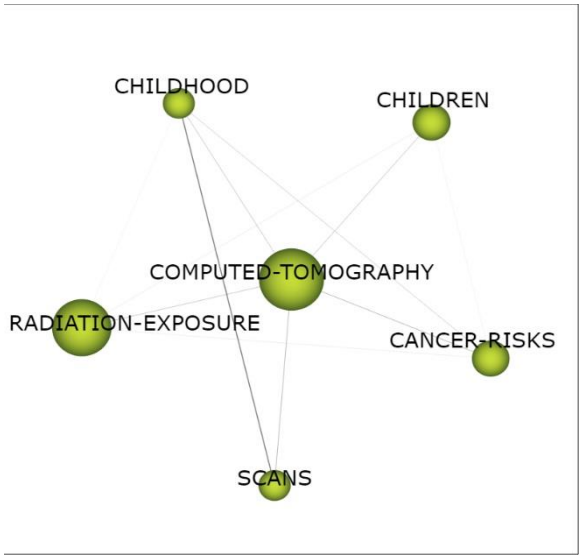


The thematic network (Figure 7) indicates relationships of three influential themes in 2010-2023. "Exposure" theme is related to "radiation protection," "ionizing radiation," "patient," "radiation," and "risk" themes. Additionally, the "computed tomography" theme is related to "children," "cancer risks," "scans," "radiation exposure," and "childhood" themes. Lastly, the "awareness" theme is related to "doctors," "knowledge," "attitudes," "physicians," "residents," and "knowledge" themes.

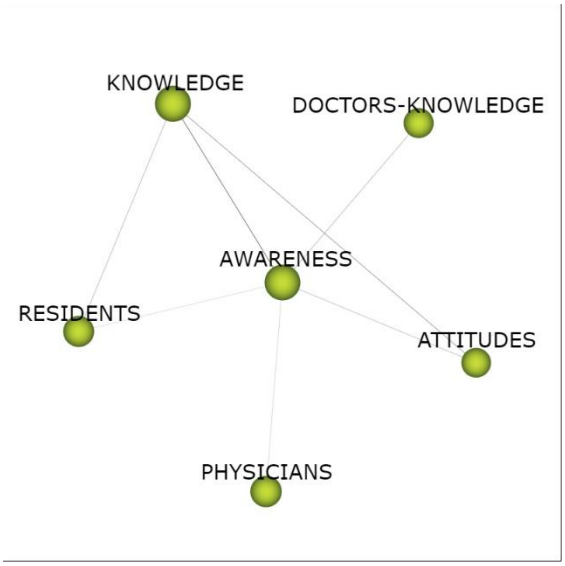
Figure 7. Thematic Network of the Three Influential Themes in 2010-2023



Exposure



Compute Tomography

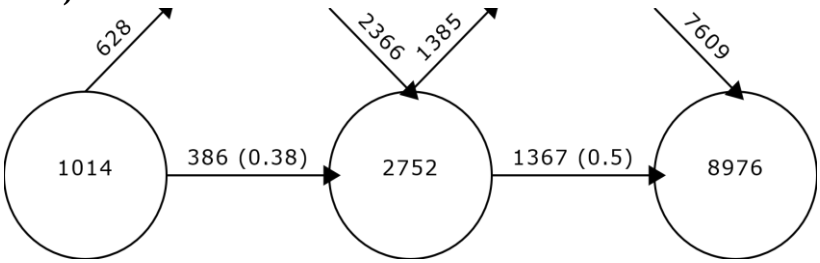


Awareness

3.5. Thematic Relationships

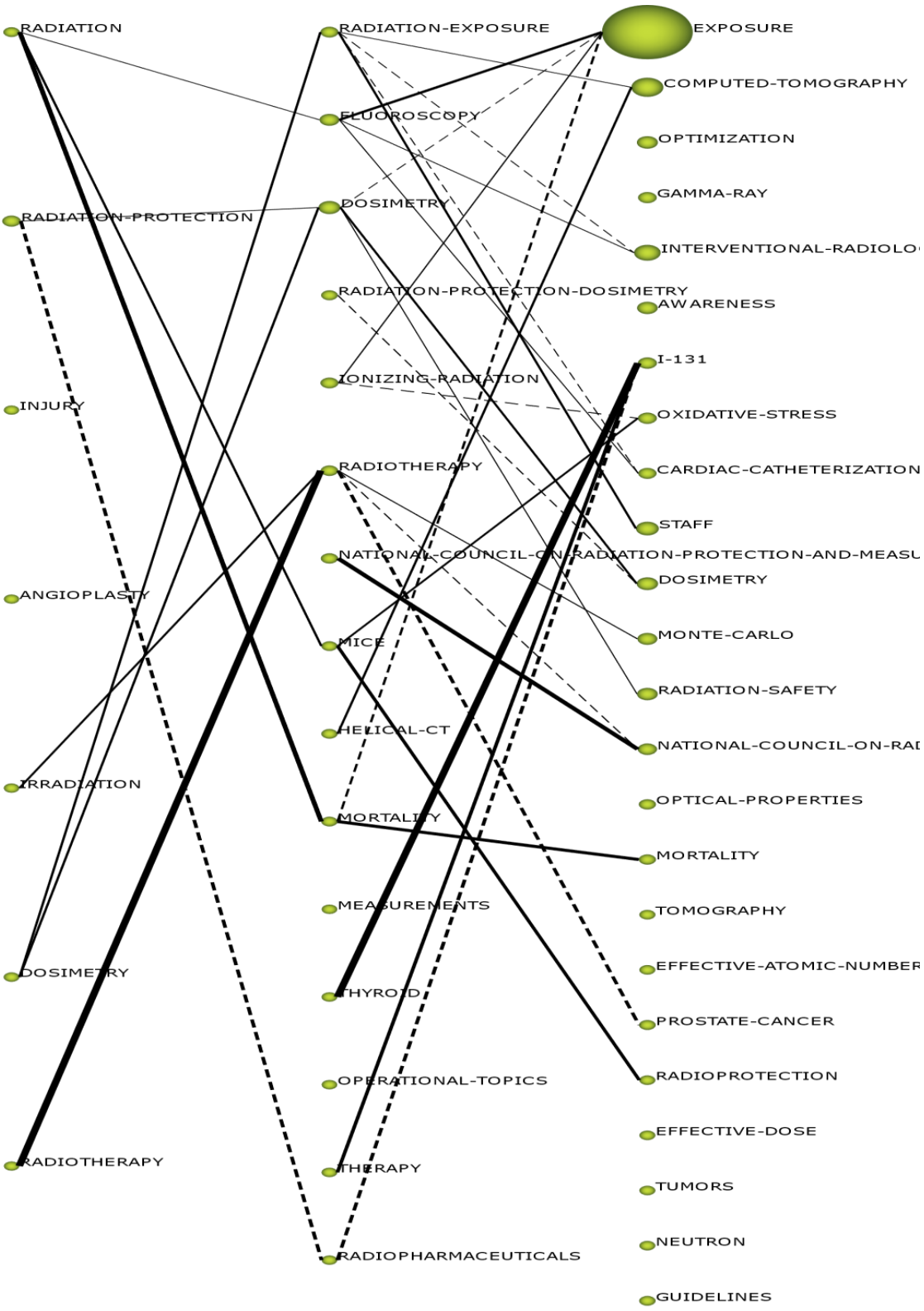
The keyword number in the publications in 1990-1999 was 1014, 386 (38%) keywords in this period also remained in use in 2000-2009. The keywords in 2000-2009 increased to 2752, with 2366 new ones. 1367 (50%) keywords in 2000-2009 remained in use in 2010-2023, and the keywords in 2010-2023 increased to 8976 with 7609 new ones (Figure 8).

Figure 8. Overlap Map of Keywords During Periods the Periods (1990-1999, 2000-2009, 2010-2023)



The thematic development map (Figure 9) presents the relationships between the themes in these three periods. Based on this map, "radiation" in the first period is related to "mortality" in the second and the same name theme in the last period. The "Radiotherapy" theme in the first period is in the second, and it has the same name. A strong relationship between these two periods was determined as well. The "Radiotherapy" theme is also related to the "prostate cancer" theme. "Dosimetry" in the first period is also included in the subsequent two periods and is associated with "radiation exposure" in the second period. "Radiation exposure" in the second period" is related to "staff" in the last period. The themes "National Council on Radiation Protection" and "measurements" are seen in the last two periods and have a strong relationship between these periods. The "Mice" theme in the second period is associated with "radiation" in the first period and "oxidative stress" and "radioprotection" themes in the last period. The "Thyroid" theme in the second period is strongly associated with the theme of "I-131" in the last period. The theme of "I-131" in the last period is also related to the themes of "therapy" and "radiopharmaceuticals" in the second. "Radiation" in the first period is related to the theme "fluoroscopy" in the second. The theme "fluoroscopy" is related to "cardiac catheterization," "exposure," and "interventional cardiology" in the last.

Figure 9. Thematic Development Map during the Periods (1990-1999, 2000-2009, 2010-2023)



IV. DISCUSSION

This study is the first bibliometric research to evaluate publications on radiation safety in medicine in the literature. The number of studies and topics in this field is increasing rapidly along with technology over time.

Examining the most influential publications in 1990-2023 on radiation safety in medicine, the first two are within the scope of Gent4, publicly known as the CERN project (Conseil Européen pour la Recherche Nucléaire). This project implements experiments for the simulation of the passage of particles through matter. The project reveals findings regarding radiation safety and optimization as a result of experiments (Allison et al., 2006; Allison et al., 2016). In the third most influential publication, Mettler Jr et al. (2009) drew significant attention to medical radiation safety, revealing the rate of medical radiation in the USA and worldwide. This study showed that medical radiation increased 10-fold between 1950 and 2006, and medical radiation per capita increased 6-fold between 1980 and 2006. The study conducted by Bolch et al. (2009) presented standards of dosimeters to measure medical radiation exposure in line with the recommendations of the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine and The International Commission on Radiological Protection (ICRP). The other most cited study is the cohort study conducted in 15 countries by Cardis et al. (2005). This study indicates that even low levels of medical radiation carry cancer risk. In summary, most influential studies focused on new findings (Allison et al., 2006; Allison et al., 2016), standards (Bolch et al., 2009), risks (Mettler Jr et al., 2009), and health problems (Cardis et al., 2005) of medical radiation. The publications can be considered as the basis for radiation safety.

Evaluating the most productive authors, M.I.Sayyed comes to the fore with shielding and software publications for medical radiation safety (Google Scholar, 2023). Another productive author, E. Vano, has many publications on radiation dose management, especially in interventional cardiology. The most notable publications are ICRP publications (Complutense University of Madrid, 2023). The ICRP-135 publication regarding diagnostic radiation level (DRL) primarily guides this field. DRL is an effective quality management tool in medical radiation optimization (Vañó et al., 2017).

In 1990-1999, the themes of "dosimetry," "exposure," and "radiation protection" were emerged. The themes can be grouped under the concept of occupational safety. In the literature, radiation dose monitoring and follow-up are essential for employee and patient safety (Martin & Sutton, 2015; Miller, 2020; Vañó et al., 2017). However, this period focused mainly on occupational safety rather than patient safety against medical radiation.

Two of the themes related to radiation safety were "shielding" and "X-ray." Traditional lead "Shielding" is one of the most effective passive methods in radiation safety (Bartal et al., 2018). Many studies aim to find lighter, more protective shield materials (Adlienė et al., 2020; Cataldo & Prata, 2019). The second theme that gained importance in the 1990s was "angioplasty." Researchers are thought to have focused on this theme because this treatment method in cardiology involves high radiation exposure (Picano et al., 2014).

In 2000-2009, the number of studies on radiation safety increased significantly. The theme of "fluoroscopy" was the basic theme. Interventional radiology, an "angioplasty" theme in the 1990s, continued to attract the attention of researchers as "fluoroscopy" in 2000-2009. The "NCRP" theme also appeared as an advanced theme in this period. This finding might indicate that researchers take NCRP publications as guides and gain importance. In addition, the focus on "helical CT" in the same period can be explained by the significant radiation exposure this diagnostic method causes (Armao & Smith, 2014; Miller, 2020; Picano et al., 2014)., as seen in "fluoroscopy" and "angioplasty" (Picano et al., 2014). Another influencing factor can be the integration of radiation safety in healthcare services with international and national standards (IAEA, 2016; ICRP, 2007a; TBMM, 2000; WHO, 2024). Additionally, the spread of quality and accreditation programs in health services might be another important factor. One of the Joint Commission International (JCI) hospital accreditation standards is

Radiology and Diagnostic Imaging Services (AOP.6.2), which aims to ensure the safety of patients, employees, and the public in diagnostic and interventional radiology (JCI, 2021).

The number of publications on radiation safety continued to increase in 2010-2023. Looking at the prominent themes, "computed tomography," "interventional radiology," and "cardiac catheterization" attracted scientists' attention in 2010-2023. Academicians examined high radiation exposure modalities more frequently in terms of radiation safety (Armao & Smith, 2014; Miller, 2020; Picano et al., 2014). In 2010-2023, "optimization" and "awareness" were the developing engine themes. While passive radiation protection measures such as "shielding" came to the fore in the 1990s, active radiation protection measures such as "optimization" came to the fore in the literature after 2010. This finding is consistent with the "National Council on Radiation Protection" theme seen in the last two periods after 2000, an organization leading radiation optimization in the medical field. In addition, E. Vano, one of the most prolific authors, the author of ICPR 135, a guide for diagnostic radiation levels (DRL) in radiation optimization, indicates "optimization" gained importance in radiation safety after 2010.

The increase in the number of catheter laboratories and the procedures performed in these units, such as angiography and percutaneous intervention, might have contributed to this publication's number rise on radiation safety of interventional radiology and cardiac catheterization. According to the American Hospital Association, the number of catheter laboratories increased by 21% between 2003 and 2011 (Langabeer et al., 2013). A study in Italy covering 2010-2015 found a significant increase in primary percutaneous interventions. Additionally, in the same study, the number of structural heart interventions such as TAVI and Mitra Clip doubled, attributed to the rise in the number of heart centers in Italy (Berti et al., 2017). In India, a study involving 704 hospitals showed a 13.14% annual increase in percutaneous interventions (Arramraju et al., 2020). Similarly, a national study in Austria from 2012-2018 found a 58% increase in number of catheter laboratories and a 20.8% increase in percutaneous interventions (Muhlberger et al., 2020). These findings indicate a steady rise in interventional radiology and cardiology centers and procedures over the past 30 years, consistent with the increased focus on radiation safety in these fields.

The relationship between the themes of "mortality," "mice," and "atomic bomb survivors" highlights the significant challenges in studying the effects of radiation on human health. Because conducting intervention-control studies on humans is impractical and unethical, researchers rely on alternative sources for their findings. One primary source of data is the long-term follow-up studies of survivors of the atomic bombings in Hiroshima and Nagasaki, Japan (Douple et al., 2011; Grant et al., 2015; Neriishi et al., 2012). These studies provide valuable insights into the long-term health effects of radiation exposure as they track the health outcomes of individuals exposed to varying levels of radiation during the bombings (Neriishi et al., 2012; Preston et al., 2007). These survivors have been the subjects of extensive research over the decades, yielding critical information on radiation-induced cancers, genetic effects, and other health impacts (Douple et al., 2011; Kamiya et al., 2015; Little, 2009; Neriishi et al., 2012; Preston et al., 2007).

Additionally, animal experiments, particularly in mice, play a crucial role in understanding radiation effects on health. Mice are often used in these studies due to their genetic similarities to humans and their relatively short lifespans, which allow researchers to observe long-term effects more quickly (Uma Devi et al., 2000; Vrinda & Devi, 2001). These experiments can provide controlled environments to study specific variables and outcomes, contributing to a more comprehensive understanding of radiation's biological effects. Additionally, organizations responsible for radiation safety, such as the International Commission on Radiological Protection (ICRP), often base their guidelines and safety standards on the findings from both atomic bomb survivor studies and animal research. These findings help establish exposure limits, safety protocols, and risk assessment models to protect public health and ensure safe practices in environments where radiation is present (ICRP, 2007a; Ozasa et al., 2016; Pawel & Puskin, 2012; Stewart et al., 2012). Current findings about risks and precautions of radiation safety in healthcare are based mainly on the results of studies with atomic bomb survivors and animal experiments.

Additionally, the "awareness" theme is the motor theme in this last period. "Optimization" requires proactive knowledge and attitude for radiation safety. From this perspective, academic focus on "awareness" is consistent with "optimization." The relationship between "awareness," "knowledge," and "attitude" themes supports this finding. This finding was particularly consistent with establishing patient dose monitoring systems and active optimization approaches in many countries (Fukushima et al., 2012; McCollough, 2010; Paulo et al., 2020; Vassileva & Rehani, 2015). The International Commission of Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) have widely recommended radiation optimization in healthcare (IAEA, 2023; Vañó et al., 2017). For example, when the necessary optimization was made in interventional cardiology, the resulting radiation dose could be reduced by up to 95% (Fiorilli et al., 2020; Kumar & Rab, 2016).

A relationship was detected between the "radiation" and "mortality" themes. This finding is consistent with literature about the adverse effects of radiation on health (Bennardo et al., 2021; Purohit et al., 2021). Additionally, there is a relationship between the themes of "radiation," "fluoroscopy," "exposure," "cardiac catheterization," and "interventional radiology." This finding is consistent with the increasing academic interest of academics in the interventional catheter laboratory over time. This interest is because the interventional radiology modality is a riskier field in terms of radiation (Armao & Smith, 2014; Miller, 2020; Picano et al., 2014).

V. CONCLUSION

When publications on radiation safety in medicine between 1990 and 2023 were examined, a changing trend can be seen in radiation safety in medicine from an employee-oriented approach to a patient and employee-oriented approach and from passive protection measures to passive and active protection measures. Radiation safety in medicine focused on occupational safety and passive protection methods against radiation in the first periods. CT and interventional radiology modalities that cause high radiation exposure gained importance in later periods. After the 2000s, active prevention methods, along with optimization and awareness, were the focus points. Patient safety also gained importance with optimization following occupational safety after 2010. Radiation optimization and awareness are recent fields of focus in radiation safety in medicine.

Based on these research results,

- Healthcare managers and professionals are recommended to focus on radiation optimization in the medical field for radiation safety. Current and widespread radiation optimization tool DRL can be considered a priority.

- DRL, an essential quality tool in radiation optimization, is unavailable in Türkiye. Health politicians and health managers are recommended to take the initiative to optimize medical radiation. Particularly, modalities and indications that require high radiation should be considered.

- It is recommended that academics focus on optimization and awareness issues regarding radiation safety, which will become more critical in the future. Areas with high radiation, such as CT and interventional radiology, should be prioritized.

Ethical approval: Ethical approval was not required for this study because it was conducted with publicly available WOS data.

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